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A review on utilisation of biomass from rice industry as a source of renewable energy

Jeng Shiun Lim, Zainuddin Abdul Manan*, Sharifah Rafidah Wan Alwi, Haslenda Hashim

Process Systems Engineering Centre (PROSPECT), Faculty of Chemical Engineering, Universiti Teknologi Malaysia, 81310 Johor Bahru, Johor, Malaysia

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A B S T R A C T

Volatile oil price and growing emphasis on environmental conservation have stimulated the development and utilisation of biomass as a vital source of renewable energy. In reducing the global dependency on fossil fuels, rice husk and rice straw which are the widely abundant agricultural wastes from the rice industry have a vital role to play. This paper reviews the key aspects of the utilisation of rice husk and rice straw as important sources of renewable energy. The paper provides some essential background information that includes the physical and chemical characteristics that dictates the quality of these rice biomasses. This paper also describes the various chemical and physical pretreatment techniques that can facilitate handling and transportation of rice straw and husk. Finally, the paper presents the state-of-the-art on thermo-chemical and bio-chemical technologies to convert rice husk and rice straw into energy.

Contents

1. Introduction

Industrialisation and population growth are among the leading factors for the rising trend in the global energy demand. By the year 2030 [1], the global energy demand is forecasted to increase by 43.64% from the current total of 472 quadrillion Btu to 678 quadrillion Btu, assuming business as usual and no changes in the current laws and policy governing energy consumption. It is also predicted that fossil fuel (oil, natural gas and coal) will still remain as the dominant source of energy by the year 2030. Heavy reliance on fossil fuel contributes towards fossil fuel depletion and climate change [2]. These concerns have stimulated the development

* Corresponding author. Tel.: +60 7 5535478; fax: +60 7 5581463.
E-mail address: zain@cheme.utm.my (Z. Abdul Manan).

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Nomenclature

SSA	Sub-Saharan African
CO_2	carbon dioxide
CO	carbon monoxide
NO_x	nitrogen oxides
SO_2	sulphur dioxide
PM	particulate matters
PCDDs	polychlorinated dibenzo-p-dioxins
PCDFs	polychlorinated dibenzofurans
HHV	higher heating value
MFF	multi fuel fouling
CDM	clean development mechanism
CFB	circulating fluidised bed
IC	internal combustion

and utilisation of alternative energy such as biomass, solar, wind, and hydro. Among these renewable energies, agriculture residue (biomass) has become an important source of fuel since the early 1970s. However, due to the drop in oil prices in 1986 [3], agriculture residue lost its economic competitiveness to fossil fuels.

Volatile oil price and rising concern for environmental protection have once again turned the attention of the world towards alternative energy sources. In addressing the rapidly growing needs for alternative energy, biomass has been considered as one of the most promising sources of renewable energy due to its near-carbon neutrality and due to the ample availability of various sources of biomass [4]. In the recent years, utilisation of agriculture waste and residues (for instance, rice husk, rice straw and bagasse) for energy generation has received a lot of attention since biomass does not threaten food supply and is therefore not the source of “food or fuel” controversy. Among the biomass resources, rice husk and rice straw are the key residues from rice crop, which is one of the world’s most important staple foods. Ample availability of rice husk and straw, coupled with the continuous development of biomass energy conversion technologies have turned rice biomasses into vital sources of renewable energy.

1.1. Origin, supply and demand of rice

Rice, a monocotyledon plant, is botanically known as *Oryza*. The genus *Oryza* consisted of two cultivated species and 21 wild species [5]. The cultivated species, *Oryza sativa* and *Oryza glaberrism* originate from Asia and Africa, respectively. *O. sativa* has superior yield and milling quality and is commercially grown in 112 countries from all continents. In contrast, *O. glaberrism* is only grown in the West Africa region. Although categorised as a semiaquatic plant, the cultivated rice species can grow in both dry land and in deep water of up to 5 m [6].

Rice is an important staple food for approximately half of the world population [7]. Asia region alone produces over 90% of the total global rice output with China and India contributing some 28.7% and 19.5% shares of the total output, respectively (refer to Table 1). Statistics in the year 2009 shows that 196.7 million tons of paddy (unmilled rice) was harvested from 29.8 million ha of planting areas in China [8] while 133.7 million tons of paddy was harvested from 41.9 million ha of planting areas in India [8]. Although China and India are the largest rice producers in the world, their export quantities are relatively low due to the high demands from their huge population.

Rice demand is expected to remain strong in the next few decades due to the economic and population growths in many countries across Africa and Asia [9]. Economic growths in these under developed countries tends to shift the peoples’ diet from mainly consisting of coarse grains and sweet potatoes to rice, subsequently leading to the increase in the per capita rice consumption. However, continued economic growth is expected to further shift the countries’ eating preference from rice to a more balanced diet that may include meat, vegetable and fruits. This will lead to a decline in the per capita rice consumption as experienced by China, Thailand, South Korea, Japan, and Taiwan. Nonetheless, the per capita fall in rice consumption in these countries will be compensated by the growth in the per capita rice consumption of other countries including in the United States, India, Vietnam, Myanmar, the Philippines, Bangladesh, and in the Sub-Saharan African countries [10]. Timmer et al. predicted that by 2020, the total rice consumption will be 450 million tons (milled basis), a 6.6% growth as compared to 422 million tons in 2007 [11]. Overall, the rice industry will remain sustainable for a long time. Subsequently, the availability of rice agricultural wastes will remain high (refer to Table 1).

Vast choices of technologies are available to convert agricultural wastes from paddy into renewable energy. This paper reviews the state-of-the-art on utilisation of rice husk and rice straw for energy generation. The paper provides some essential background information that includes the physical and chemical characteristics that determined the quality of rice biomass. This paper also describes the various chemical and physical pretreatment techniques that can facilitate handling and transportation of rice straw and husk. Finally, the paper presents the conversion technologies covered in the previous research works and current applications associated with the utilisation of rice husk and rice straw as renewable energy resources.

2. Rice biomass and its utilisation

In general, agricultural wastes are biomass residues that can be divided into two categories namely the crop residues and the agro-industrial residues [12]. Crop residues refer to plant residues that remain on the field after the collection of crops. The agro-industrial residues on the other hand are the by-products of the post-harvest processes that maybe generated from the process of cleaning, sieving, and milling. In rice industry, biomass residues that are commonly utilised for energy generation are rice straw and rice husk, which are crop residue and agro-industrial residue, respectively. Rice straw is the stalk of the rice plant that is left over as waste products on the field upon harvesting of the rice grain (i.e. the seeds of rice). Rice husk is the outer layer of a rice seed. Rice husk is removed from the rice seed as a by-product during the milling process.

Table 2 gives the residue ratio for rice straw and rice husk reported by different researchers. The table shows that, for every kilogram of harvested paddy, between 0.41 and 3.96 kg of rice straw will be produced. Rice husk on the other hand accounts for between 20% and 33% of paddy weight. The annual global quantity of rice straw and rice husk generated is 685 million tons and 137 million tons, respectively. If fully converted, these amounts of rice straw can produce about 191.8 billion litres of ethanol [13], which is equivalent to 119.9 billion litre of gasoline [14].

Until today, open field burning that is often carried out after harvesting season is perhaps the most common practice of handling rice straw in many countries in Asia [15]. According to a survey, in Thailand, 90% of the rice straw collected during the peak harvesting season between November and December are burned in the open fields [16]. Similar to the rice straw, rice husk is commonly disposed via open burning in the field [17]. Such practice leads to the energy being wasted and poses environmental and health threats to the public.

Table 1
Production quantity of paddy, rice straw and rice husk [8].

Regions	Harvested quantity (million tons)	Estimated rice straw[a] (million tons)	Estimated rice husk[b] (million tons)
Africa	24.51	24.51	4.90
Americas	38.10	38.10	7.62
Asia	618.24	618.24	123.65
China	196.68		
India	133.70		
Indonesia	64.40		
Bangladesh	47.72		
Vietnam	38.90		
Europe	4.10	4.10	0.82
Oceania	0.29	0.29	0.06
World	685.24	685.24	137.05

[a] With residue ratio of 1.
[b] With residue ratio of 0.20.

Table 2
Residue ratio of rice straw and rice husk.

	Residue ratio (ton/ton)	Reference	Remark
Rice straw	1.1	[15]	
	0.623	[26]	
	1–1.5	[27]	
	0.41–3.96	[28]	
	1.53	[29]	Agricultural residue availability (in kg) per ton of grain produced
Rice husk	0.2–0.33	[28]	
	0.23	[30]	Based on processed rice
	0.25	[12]	
	0.33	[29]	Agricultural residue availability (in kg) per ton of grain produced

These rampant burning activities release pollutants such as carbon dioxide (CO_2), carbon monoxide (CO), un-burnt carbon (with trace amount of methane), nitrogen oxides (NO_x), and trace amount of sulphur dioxide (SO_2), along with other particulate matters (PM) that include polycyclic aromatic hydrocarbon *n*-alkane [18,19], polychlorinated dibenzo-p-dioxins (PCDDs), and polychlorinated dibenzofurans (PCDFs) commonly known as dioxins [20]. These air pollutants can adversely affect human health, including causing cancer. Specific researches in Japan [21] and the United States [22] associate the burning of rice straw to the asthma attacks occurring in specific regions of these countries. In addition, CO_2 emissions from these open field burning activities will accelerate the increase in atmospheric temperature and cause global warming.

Due to the health and environmental concerns, many countries have imposed new regulations to restrict field burning activities [23]. Subsequently, methods to dispose and to use rice straw and rice husk have shifted towards the global “waste to resource” agenda. Recently, rice straw and rice husk have been used as construction materials [24], for the adsorbent of heavy metals [25], and for the production of energy and fuels (see Table 7).

Although rice straw has potential to be used as a biomass source to produce renewable energy, its large scale application is rather limited as compared to the use of rice husk [31]. Utilisation of rice husk for electricity generation has been well-developed in many regions due to its wide availability at rice mills. In contrast, the procurement of rice straw is more difficult, as various logistic aspects need to be considered, including handling and collection from fields [32]. Hence, it is vital to consider the logistic factors to assess the economics of using rice straw as a source of energy.

3. Quality of rice biomass

Rice straw and rice husk, like many lignocellulosic biomasses, possess several properties that makes them suitable as feedstocks for bio-chemical conversion to fuel such as ethanol. Alternatively, rice straw and rice husk can be combusted to produce heat and electricity. Table 3 shows the composition of rice straw and rice husk consisting of hemicellulose and cellulose which can undergo hydrolysis into fermentable sugars (carbohydrates) and further conversion into ethanol [33] or hydrogen [34].

Table 4 shows the other important properties of rice husk and rice straw. The higher heating value (HHV) indicates the energy content of a given biomass. The typical HHV of agricultural residue ranges between 15 MJ/kg and 17 MJ/kg. The HHV of rice husk and rice straw are 15.84 MJ/kg and 15.09 MJ/kg, respectively. The HHV influences the ash content and extractive content of biomasses. Demerbas (2002) reports that while the extractive content increases the HHV of a biomass, the ash content reduces it [36].

The chemical composition of a biomass feedstock can also influence its combustion efficiency. High alkali content (Na and K) and presence of phosphorous in rice husk and rice straw can decrease the melting temperature of ash. Besides, the low melting temperature of rice husk may lead to fouling and corrosion of heat transfer surfaces, and the possibility of agglomeration in a fluidised bed [37]. However, Skrifvars [38,39] reported that rice husk is classified as low fouling by multi fuel fouling (MFF) index, due to the high content of ash.

4. Pre-treatment of rice biomass

Rice straw and rice husk must be pre-treated carefully upon collection from fields and prior to conversion process. This is in order to minimise the transportation costs of the raw materials and the handling costs to produce the end products.

Table 3
Composition of rice straw and rice husk [35].

Biomass	Rice straw (%)	Rice husk (%)
Hemicellulose	35.7	28.6
Cellulose	32.0	28.6
Lignin	22.3	24.4
Extractive matter	10.0	18.4

Table 4
Properties of rice residue [40].

	Rice husk	Rice straw
Higher heating value (constant volume)		
MJ/kg	15.84	15.09
Btu/Ib	6811.00	6486.00
Proximate analysis (% dry fuel)		
Fixed carbon	16.22	15.86
Volatile matter	63.52	65.47
Ash	20.26	18.67
Total	100.00	100.00
Ultimate analysis (% dry fuel)		
Carbon	38.83	38.24
Hydrogen	4.75	5.20
Oxygen (diff.)	35.47	36.26
Nitrogen	0.52	0.87
Sulphur	0.05	0.18
Chlorine	0.12	0.58
Ash	20.26	18.67
Total	100.00	100.00
Elemental composition of ash (%)		
SiO_2	91.42	74.67
Al_2O3	0.78	1.04
TiO_2	0.02	0.09
Fe_2O_3	0.14	0.85
CaO	3.21	3.01
MgO	<0.01	1.75
Na_2O	0.21	0.96
K_2O	3.71	12.30
SO_3	0.72	1.24
P_2O_5	0.43	1.41
CO_2/other		
Total	100.64	100.00
Undetermined	0.64	2.68

4.1. Pre-treatment prior to thermo-chemical conversion

The typical pre-treatment technologies include sizing, leaching (commonly known as washing), and palletisation. From the physical perspective, the high volatility and low density of rice husk and rice straw can cause challenges in handling and transportation. However, it has been proven that these challenges can be overcome by densification of the biomass fuels.

Densification techniques can be categorised into two: pressure agglomeration and tumble agglomeration. Pressure agglomeration involves the mechanical compression [41] of biomass materials via extruding, pelleting or briquetting, whereas in tumble agglomeration, binding agents are required [42].

Generally, densification improves the initial bulk density of biomass from 40–200 kg m^{-3} to a final density of 600–800 kg m^{-3} [43]. To produce good quality products, generalised optimum densification conditions [42] can serve as a reference, coupled with good design of machine [44]. Specific results show that during thermal compression, the mixing of rice bran can promote the densification process of rice straw [45]. Densified biomass can minimise the cost of handling, storage and transportation. Researches also indicate that homogenously densified biomass fuel, such as straw pallet, is a key component in realising full automatic operation and complete combustion in furnaces [46].

Sizing refers to the process of reducing the size of rice straw and rice husk, with the aim to improve boiler efficiencies. In general, biomass fuel with small-sized particles provides higher burning rates as well as ignition front speeds, leading to better combustion efficiency [47]. For instance, rice husk, cut straw and sawdust can provide boiler efficiency of up to 75%, a 5% improvement over the large particle biomass feedstock, for instance, palm shell and wood chips [48]. Further researches show that fine-sized straw improve the combustion behaviour [49] and energy conversion efficiency [50].

Looking from the perspective of chemical properties, the high alkali content of rice straw and rice husk can ultimately lead to slagging and fouling problems in combustion equipment. Hence, pre-treatment of these resources becomes an integral part of utilising these resources as fuel.

Leaching process can remove unwanted substances in the rice straw. It can reduce slagging, fouling as well as corrosion [51] problems in furnaces system and subsequently extend the operating life of a boiler. Studies have shown that distilled water or tap water can efficiently reduce the quantity of potassium, sodium and chlorine in the rice straw [52]. Researches have also demonstrated that it is economically viable to utilise leached rice straw as a fuel in commercial combustion power systems [53].

4.2. Pre-treatment prior to bio chemical conversion

In biochemical conversion, pretreatment of lignocellulosic biomass is an essential step that emphasises on the removal of lignin network. Pretreatment contributes towards a huge portion of the cost throughout the process of converting lignocellulosic biomass into fermentable sugar [54]. The cellulose and hemicellulose components of rice biomass are embedded within the lignin network consisting of polysaccharide layers that prevent the enzymatic hydrolysis. Hence, to expose the cellulose and hemicellulose for enzymatic action, and subsequently increase the bioconversion efficiency, the lignin network must be removed with proper pretreatment [55].

In relation to biochemical conversion of cellulosic biomass into ethanol, Sun and Cheng provide an overview on the most promising pretreatment techniques that include dilute acid, sulphur dioxide, ammonia expansion, aqueous ammonia and lime [56]. Their study suggested that pretreatment is the key cost of the overall bioconversion process. In a later research, Mosier et al. reviewed several pretreatment methods, with emphasis given on its fundamental modes of action and relevant process parameter [54].

Taherzadeh and Karimi [57] described the key effective parameters in pretreatment of lignocelluloses, such as crystallinity, accessible surface area, and protection by lignin and hemicellulose. The researchers also highlighted several pretreatment methods along with their effects in improving bioconversion [57].

Hendriks and Zeeman [58] reviewed the effects of different pretreatment methods on the cellulose, hemicellulose and lignin. The authors emphasised on the efficiency of several pretreatment methods, including steam pretreatment, lime pretreatment, liquid hot water pretreatments and ammonia-based pretreatments that are aimed at dissolving the hemicellulose, modifying the lignin structure, and subsequently improving the hydrolytic enzymes action on cellulose [58].

In short, the pretreatment of lignocellulosic biomass aims to increase biomass surface area, decrease crystallinity of cellulose, eliminate hemicellulose, and break the lignin seal. With the vast choices of pretreatment technologies available, a thorough assessment must be made in order to ensure that the economic trade-off associated with pretreatment handling and transportation costs are considered.

5. Technologies to convert rice biomass into energy

In general, biomass can be converted into energy products via two processes:

(a) Thermo-chemical process.
(b) Bio-chemical process.

5.1. Thermo-chemical process

Thermo-chemical processes can be divided into two categories. The first category involves direct utilisation of biomass as fuel for combustion, and subsequently for heat and electricity generation. The second category involves converting biomass into other useful forms of energy products prior to its utilisation as a source of energy. Goyal et al. provided an overview on various thermo-chemical technologies, including direct combustion, gasification, liquefaction, hydrogenation, with pyrolysis discussed in more detail [59].

5.1.1. Direct combustion

In direct combustion, biomass is utilised as a fuel in a combustion boiler to produce steam (a heat source) in the presence of sufficient air in the combustion chamber. Heat and electricity can be simultaneously generated (cogeneration) using turbines. Generally, biomass combustion technologies can be categorised into the fixed bed and fluidised bed combustion systems. Natarajan et al. [64] provides an overview on the previous work on combustion of rice husk in fluidised bed combustion system. Table 5 provides a summary of researches related to direct combustion of rice husk and rice straw.

Wibulswas et al. [149] evaluated the economic feasibility of installing steam power plants in a rice mill by comparing a gasifier-internal combustion engine system and a boiler-turbine system. The results suggest that both systems are economically feasible to meet the energy demand.

Sookkumnerd et al. [60] developed an economic model to identify the internal rate of return on the investment of rice husk-based steam engine for rice mills in Thailand. The results show that it is cost-effective to install steam engines in rice mills with daily capacities of between 45 and 120 tons [60]. In a later research, the authors incorporated the revenue from the sales of excess electricity to the grid. The study demonstrated that the incorporation of grid-connected generators into the husk-fuelled stream engine gives a positive impact on the financial performance of rice mills with daily capacities of 120 tons [61].

Later, Bergqvist et al. [150] evaluated the economic feasibility of utilising rice husk to fulfil the electricity demand of rice milling industry. The authors considered three power plants with different capacities to meet the various energy demands. They also considered the lifetime costs, energy savings from cogeneration system, sales of rice husk ash and assessed the potential to implement the clean development mechanism (CDM). The study suggested that for large plants, electricity generation would be economically feasible, provided that the revenues from ash sales or CDM are included. However in smaller plants, both ash sales and CDM need to be incorporated in order to ensure financial viability.

To date, technology of utilising rice husk to produce heat and electricity has been well established. Carlos and Ba Khang [62] pointed out that in South East Asia alone, there are 44 rice husk-based cogeneration projects. Some developers prefer to use rice husk as a single fuel, due to the potential revenue generated from rice husk ash with high silica content. Note that more than 80% of these projects are capped at 10 MW due to the limited availability of rice husk within the perimeter of the cogeneration facility [62].

5.1.2. Gasification

During a gasification process, biomass is directly converted to synthesis gas (syngas) in a gasifier under a controlled amount of air. Syngas can be used in internal combustion (IC) engine to produce heat, or in a cogeneration system to produce heat and electricity. Table 6 is a summary of researches on gasification system that uses rice husk and rice straw as biomass fuels.

Previously, Kapur et al. calculated the unit cost of electricity of using rice husk gasifier based power generation system and evaluated its financial feasibility with utility supplier and diesel-generated electricity [76]. Abe et al. [77] discussed the potential of rural electricity generation via biomass gasification system. The results suggest that even though agricultural residues such as rice husks may contain high energy potential, however, to supply a biomass gasification system in the long term may require tree farming in order to provide sufficient amount of resources [77]. These researches imply that the feasibility of these large scale projects is greatly dependent on the plant location that affects the resource availability and the incurred logistic costs of the selected biomass feedstock.

On an industrial scale, biomass gasification and power generation systems have been well-established. Table 7 shows the list of rice husk-based biomass gasification and power generation systems installed by a China company. The capacities of these projects range between 200 and 10,000 kW.

5.1.3. Pyrolysis

Pyrolysis is a decomposition process of biomass at high temperature in the absence of air. Pyrolysis occurs under pressure and suitable typical operating temperature range between 350 °C and 550 °C. The end products are in the form of gas and liquid as well as carbon-rich solid residue. The proportion of the products depends on the operating conditions. The extreme cases of pyrolysis are termed as carbonisation, where most carbon is left in the solid residue. Bridgwater et al. highlighted the important components of the fast pyrolysis process that comprises of the main reaction systems and processes and the resultant liquid products [90].

In an earlier research, Islam and Ani [91] evaluated the economic feasibility of using fluidised bed fast pyrolysis with and without catalytic treatment to produce oil and solid char. The results show that it is economically feasible to operate a 1000 kg/h unit of the fast pyrolysis fluidised bed without catalytic treatment to produce primary pyrolysis oil with the lowest unit production cost [91].

A recent study conducted by Tewfik et al. [92] shows that the bio oil produced from a pilot scale entrained flow reactor is within the range of acceptable product characteristics. Further financial analysis shows that it is economically viable to construct a 200 ton/day of the bio oil commercial facility, based on the developed process design [92].

There have been extensive researches on the application of rice straw and rice husk in gasification technology which are still undergoing commercial development (see Table 8). Table 9 shows a number of pilot scale and lab scale biomass pyrolysis units that produces energy as products.

5.2. Bio-chemical process

The bio-chemical process routes for biomass conversion into value-added products include the production of ethanol, hydrogen as well as methane. Saxena et al. reported various bio-chemical processes and technologies to produce ethanol and hydrogen [107].

5.2.1. Anaerobic digestion

During anaerobic digestion process, microorganisms convert biomass into biogas, a mixture of methane and carbon dioxide, in the absence of oxygen. The biogas products is subsequently utilised as fuel to generate heat and energy. Angelidaki et al. provide an overview on anaerobic digestion technology [108]. Table 10 provides an overview on the researches focusing on anaerobic digestion of rice husk and rice straw.

Early researches prove the viability of anaerobic digestion for mixtures of rice straw and other organic wastes [109]. Various

Table 5
Summary of researchers on combustion of rice biomass.

Author(s)	Year	Study domain/emphasis	Reference
Miles et al.	1996	Analyse the performance of various biomass fuels with respect to fouling and scaling problems by using various combustion methods.	[63]
Natarajan et al.	1998	Provided an overview of rice husk-based combustion and gasification processes in fluidised bed reactors.	[64]
Jenkins et al.	1999	Demonstrate the technical feasibility of using leached rice straw as fuel in conventional power stations with three different combustion technologies, including a stoker-fired travelling grate, a circulating fluidised bed (CFB), and a suspension fired unit.	[65]
Jenkins et al.	2000	Investigate the financial feasibility if utilising leached rice straw as fuel for existing biomass boiler.	[53]
Bakker et al.	2002	Demonstrate that leached rice straw can be utilised as fuel in fluidised bed combustion. By pre-treat the rice husk with leached process, it can reduce the rapid and undesirable ash deposition generally associated with untreated rice straw.	[66]
Bakker et al.	2003	Investigate the feasibility of collecting naturally leached rice straw for thermal combustion process.	[67]
Albina	2003	Study the combustion efficiency and emission performance of the multiple-spouted fluidised bed under different parameters and for methods of feeding.	[68]
Permchart et al.	2003	Report the result of combustion performance of various biomass fuels, including: sawdust, rice husk and pre-dried sugar cane bagasse, in a fluidised bed combustor.	[69]
Fang et al.	2004	Experiment study on rice husk combustion in a circulating fluidised bed.	[70]
Sookkumnerd et al.	2005	Analyse the economic feasibility of rice husk based steam engines at Thailand rice mills and also determined the maximum feasible rice husk prices at different rice mills capacities.	[60]
Skrifvars et al.	2005	Report the slagging and fouling performance of rice husk when fired alone or coupled with other fuels in a fluidised-bed boiler.	[38]
Skrifvars et al.	2005	Report the results of fireside fouling measurements in a pilot-scale burning test facility and in a 157 MW_{th} full-scale fluidised-bed boiler, which the rice husk and bark was burnt in different ratios.	[39]
Kuprianov et al.	2006	Study the effects of excess air ratio on the performance of co-firing of sugar cane bagasse with rice husk in a conical fluidised-bed combustor, in respect to CO and NO emissions from the combustor, along with the combustion efficiency and heat losses.	[71]
Okasha	2007	Investigate the efficiency of staged combustion in fluidised bed for rice husk to reduce NO_x emissions, in particular, at high combustion temperatures.	[72]
Eiamsa-ard	2008	Report the combustion characteristics of rice husk in a multi-staging vortex combustor.	[73]
Madhiyanon et al.	2009	Study the combustion performance of co-firing rice husk with bituminous coal in a cyclonic fluidised bed combustor with capacity of 120 kW, along with the effects of fuel blends excess air ratio and fuel blend to combustion efficiency and emission.	[74]
Sathitruangsak et al.	2009	Study the combustion performance of co-firing rice husk with coal in a fluidised-bed combustor with a short combustion chamber.	[75]

pretreatment methods, including alkali pretreatment, heat pretreatment, size reduction, and seeding, have been explored to increase the digestibility of biomass [110]. Among these methods, alkali pretreatment is notably effective in treating lignin biomass for anaerobic digestion. He et al. [111] demonstrated that the biogas yield of sodium hydroxide-treated rice straw was improved by 27.3–64.5%. The application of small scale gas digester can be found in many developing countries, particularly in China [112], India [113], Honduras [114], Colombia, Ethiopia, Tanzania, Vietnam, Cambodia and Bangladesh [115].

5.2.2. Ethanol production from fermentation

Generally, bio-ethanol production from lignocellulosic biomass consists of three major steps, namely: (i) pretreatment, (ii) enzymatic hydrolysis and (iii) fermentation. The first step, which involves pretreatment has been discussed in the earlier section. The second step is the enzymatic hydrolysis process. This step involves conversion of cellulose into glucose, and hemicellulose into several pentoses and hexoses [125]. The glucose is finally fermented into ethanol by selected microorganism. Note that the conversion of cellulose and hemicellulose fractions of lignocellulosic

Table 6
Summary of research in rice husk and rice straw based gasification.

Author(s)	Year	Study domain/emphasis	Reference
Boateng et al.	1992	Report the data collected from a bench-scale fluidised-bed gasifier system, which utilised rice hull.	[78]
Chowdhury et al.	1994	Modelling and simulation of a down draft rice husk gasifier system.	[79]
Lin et al.	1998	Study the viability of rice husk gasification to produce syngases with a controlled temperature below 1000 K, to generate power while recovering valuable amorphous silica materials. Conduct a laboratory and benchscale rice husk gasification experiments, with the aim to develop an economical feasible process with simple operations.	[80]
Mansaray et al.	2000	Develop a robust mathematical model via ASPEN PLUS process simulation, with the aim to predict the performance of a dual-distributor-type fluidised bed rice husk gasifier in a steady state, by considering different operating conditions.	[81–83]
Wu et al.	2002	Analyse the economic feasibility of biomass gasification and power generation in China.	[84]
Yin et al.	2002	Report the design and operation of a rice husk based circulated fluidised bed gasification and power generation system located in China.	[85]
Asadullah et al.	2004	Study the gasification of rice straw and other biomass by using a dual-bed gasifier coupled with $Rh/CeO_2/SiO_2$ catalyst.	[86]
Sun et al.	2009	Report the experiment data on air staged cyclone gasification of rice husk.	[36]
Wu et al.	2009	Analyse the effects of gasification temperature, equivalence ratio, moisture content and feeding rate of rice husk on the gasification performance of a rice husk based power generation plant with 1.2 MW capacity located in China.	[87]
Liang et al.	2009	Analyse the effect of equivalence ratio on the gasification performance of two-stage rice straw gasifier developed by Shanghai Jiaotong University.	[88]

Table 7
List of installed biomass gasification and power generation system [89].

Company	Capacity (kW)	Biomass	Area	Year in operation
Huanggang Rice	1000	Husk	China	1998
Yong Yang Steel	600	Husk	China	2001
854 farms	800	Husk	China	2001
Jiansanjiang agricultural	1000	Husk	China	2001
Lee Rice Mill	200	Husk	China	2001
291 farms	1000	Husk	China	2001
Shuangqiao Rice Mill	1000	Husk	China	2001
857 farms	800	Husk	China	2001
Tieli Farm	800	Husk	China	2001
Xingkaihu agricultural	600	Husk	China	2001
Shao-Yang Farm	400	Husk	China	2001
Junchuan Farm	400	Husk	China	2001
Laos Rice Mill	200	Husk	Laos	2002
Must be high rice mill	400	Husk	China	2002
Baoquanling agricultural	1000	Husk	China	2002
Peak of the original farm	1000	Husk	China	2002
Thailand ECEC	1200	Husk	Thailand	2003
Zhejiang Changxing	800	Husk	China	2004
Xinghua	4000	Husk/straw	China	2005
Henan Xinxiang	10,000	Husk	China	2006

Table 8
Summary of research on pyrolysis of rice husk and rice straw.

Author(s)	Year	Study domain/emphasis	Reference
Rao et al.	1998	Investigate the pyrolysis rate of different biomass, including rice husk, wood, and hazelnut and olive husk and subsequently, compare with literature data.	[93]
Islam et al.	2002	Conduct a rice straw pyrolysis in a fluidised bed reactor, with silica sand and nitrogen is the bed material and fluidising gas, respectively. Identify the optimum reaction condition, and subsequently, determine the calorific value, physical properties, elemental analysis and chemical composition of the oil products (obtained during optimum reaction condition) by using Fourier transform infra-red spectroscopy (FTIR).	[94]
Chen et al.	2003	Study the parametric effects of physico-chemical pretreatment of biomass particles (rice husk and sawdust), pyrolysis temperature, residence time of volatile phase in the reactor, heating rate of the external heating furnace and improvement of the heat and mass transfer ability of the pyrolysis reactor on the gas yield.	[95]
Tsai et al.	2006	Conduct a fast pyrolysis experiment in a fixed-bed induction-heating system by utilising rice husk, sugarcane bagasse and coconut shell. Investigate the parametric effect of reaction temperature, residence time and heating rate on the yield of end product prior to the analysis of its characteristic.	[96]
Maiti et al.	2006	Produced the rice husk char under conventional process condition via fix bed pyrolysis. Investigate the characteristic of palletised rice husk char and its applicability as a solid fuel in combustion process.	[97]
Worasuwannarak et al.	2006	Focus on the gas formation during pyrolysis behaviour, by examine the water and tar formation.	[35]
Tu et al.	2007	Used a radio-frequency plasma thermolysis reactor to pyrolyse rice husk. Analysed the effects of some major system parameters on pyrolysis performance. Results showed that this method can produce better quality syngas, compared to the conventional thermal heating method.	[98]
Wang et al.	2007	Pyrolysis of rice straw via tubular reactor, and subsequently, distillate the liquid product (residue) to obtain petroleum. The optimum temperature to obtain maximum amount of residue was identified.	[99]
Tsai et al.	2007	Study the effect of reaction temperature, heating rate, holding time, nitrogen gas flow rate, along with condensation temperature and particle size on the pyrolysis product yields and subsequently, its chemical compositions.	[100]
Jung et al.	2008	Conduct the pyrolysis of rice straw and bamboo sawdust in bubbling fluidised bed equipped with a char separation system. Investigate and report the effects of process conditions on the production of bio-oil, along with the efficiency of char removal system.	[101]
Wannapeera et al.	2008	Study the product yield of fast pyrolysis in a drop-tube/fixed-bed reactor by utilising various biomass, including rice straw, rice husk and corncob during.	[102]
Lu et al.	2008	Perform fast pyrolysis of rice husk via an intermediate autothermal pyrolysis set to produce bio-oil. And subsequently, analyse its elemental and chemical composition, basic fuel properties, distillation and thermogravimetric properties, along with ageing and lubrication properties. Also investigate the effects of methanol addition on some properties of the bio-oil.	[103]
Heo et al.	2010	Study the pyrolysis of rice husk under various process conditions (feed rate, temperature, flow rate, and fluidising medium) in a fluidised bed, prior to the characteristic study of its product, which is bio-oil.	[104]
Huang et al.	2010	Report the study of rice straw based microwave-induced pyrolysis to produce hydrogen gas. Also evaluate the composition and energy balance of the material and product gas.	[105]
Chen et al.	2011	Conduct rice husk based fast pyrolysis in a 1–5 kg/h bench-scale fluidised-bed reactor to produce high quality bio-oil. Filter the solid particles and bio-char by analysing the effect of hot vapour filtration (HVF).	[106]

Table 9
Worldwide biomass pyrolysis units.

Reactor design	Capacity (dry biomass feed)	Organisation or company	Products
Fluidised bed	400 kg/h (11 tons/day)	DynaMotive, Canada	Fuel
	250 kg/h (6.6 tons/day)	Wellman, UK	Fuel
	20 kg/h (0.5 tons/day)	RTI, Canada	Research/fuels
Circulating fluidised bed	1500 kg/h (40 tons/day)	Red Arrow, WIEnsyn design	Food flavourings/chemicals
	1700 kg/h (45 tons/day)	Red Arrow, WIEnsyn design	Food flavourings/chemicals
	20 kg/h (0.5 tons/day)	VTT, Finland Ensyn design	Research/fuels
Rotating cone	200 kg/h (5.3 tons/day)	BTG, Netherlands	Research/fuels
Vacuum	3500 kg/h (93 tons/day)	Pyrovac, Canada	Pilot scale demonstration/fuels
Other types	350 kg/h (9.3 tons/day)	Fortum, Finland	Research/fuels

Table 10
Summary of researches on anaerobic digestion of rice husk and rice straw.

Author(s)	Year	Study domain/emphasis	Reference
Kalra et al.	1986	Study the anaerobic digestion performance of rice husk and straw in 190-l metallic digester.	[116]
Zhang et al.	1999	Study the effects of pretreatment techniques and process condition on the conversion of rice straw into biogas via anaerobic-phased solids digester system (APS-digester system).	[117]
Zhang et al.	2008	Investigate the effects of process condition on the untreated straw conversion to biogas in dry anaerobic digestion technology with leachate circulate.	[118]
He et al.	2008	Study the mechanisms of biogas yield enhancement via solid-state sodium hydroxide pretreatment.	[111]
He et al.	2009	Analyse the effects of sodium hydroxide's main compositions and extractives on biogas yield enhancement.	[119]
Xiao et al.	2009	Investigated the effects of various leachate recycle volumes and methods on biogas production from rice straw with dry anaerobic digestion.	[120]
Chen et al.	2009	Conducted a bench-scale experiment based on anaerobic co-digestion process of rice straw and swine faeces in a fed-batch single phase reactor under mesophilic condition.	[121]
Iyagba et al.	2009	Studied the laboratory scaled co-digestion of cow dung with rice husk to produce biogas.	[122]
Lei et al.	2010	Report the performance of rice straw based anaerobic digestion with acclimated sludge at room temperature and various amount of phosphate.	[123]
Lianhua et al.	2010	Analyse the effects of solid concentration under various temperatures on anaerobic digestion efficiency of rice straw.	[124]

biomass such as rice straw and rice husk, can be achieved either by simultaneous saccharification and fermentation (SSF) or separate enzymatic hydrolysis and fermentation. Binod et al. [31] provide an overview on the potential technologies to produce ethanol from rice straw. Chen and Qiu discussed their group's recent research advances in ethanol production technologies from rice straw that are based on fractional conversion [126].

Kaylen et al. [127] developed a mathematical programming model to evaluate the financial feasibility of converting lignocellulosic biomass into ethanol. The authors suggested that by considering the co-production of higher-value chemicals along with ethanol [127] can potentially make ethanol competitive with gasoline. On the other hand, Gnansounou and Dauriat [128] took a different approach by using Value Engineering and Target Costing method. They highlighted the impact of feedstock towards the overall lignocellulosic ethanol production cost, and the importance of utilising all resources in the most efficient way [128].

In the past few decades, even though there have been extensive research progress and on the utilisation of lignocellulosic feedstock such as rice straw to produce ethanol (refer to Table 11), however, its commercialisation status has not been fully realised. Sukumaran et al. [129] reported that although ethanol production from lignocellulosic biomass has tremendous potential to contribute towards fulfilling the energy demand of India, however, the relevant technologies are under the initial phase of development [129]. The authors highlighted the need to improve the whole cycle of ethanol production steps and to develop economically feasible integrated production systems [129] in order to realise the full potential of ethanol production in the industrial scale. Such limitation also applies in the context of China where the capacity for ethanol

Table 11
Summary of researches on rice biomass based fermentation to produce ethanol.

Author(s)	Year	Study domain/emphasis	Reference
Hoshino et al.	1997	Study the delignified rice straw based ethanol production in a combination of two reversibly soluble-auto precipitating enzymes and *Pichia stipitis* cell in a continuous fermentation system.	[131]
Nakamura et al.	2001	Report the utilisation of enzymatically treated steam-exploded rice straw to produce ethanol via extractive fermentation.	[132]
Saha et al.	2004	Evaluate the effects of enzymatic saccharification (45 °C, pH 5.0) and dilute acid sulphuric pretreatments of rice husk at varied temperature (120–190 °C) on the conversion of cellulose and hemicellulose to monomeric sugars.	[133]
Tian-xia et al.	2005	Study the fermentation of hydrolysated rice husk powder prior to optimise the process condition.	[134]
Karimi et al.	2006	Study the simultaneous saccharification and fermentation with *Mucor indicus*, *Rhizopus oryzae*, and *Saccharomyces cerevisiae* of rice husk to produce ethanol, prior to the comparison with pure cellulose, Avicel.	[135]
Patel et al.	2007	Report a preliminary investigation on the agricultural wastes (rice husk and bagasse) based on microbial pretreatment and fermentation.	[136]
Saha et al.	2008	Study the effects of lime pretreatment and enzymatic on the conversion of rice husk cellulose and hemicellulose to monomeric sugars.	[137]
Oberoi et al.	2010	Investigate the simultaneous saccharification and co-fermentation of rice straw with hydrolysate-adapted *Candida tropicalis* to produce ethanol.	[138]

Table 12
Summary of researches on fermentation of rice biomass to produce hydrogen.

Author(s)	Year	Study domain/emphasis	Reference
Kumar et al.	2001	Develop an immobilised *Enterobacter cloacae* IIT-BT 08 to produce hydrogen continuously. The tested materials include rice straw, bagasse and coir.	[141]
Lo et al.	2008	Analyse the cellulose hydrolysis activity of hydrolysed carboxymethyl cellulose, rice husk, bagasse and filter paper by two mixed bacterial consortia (NS and QS), prior to the conversion from cellulose hydrolysate into hydrogen via seven hydrogen producing bacterial isolates (mainly *Clostridium* species).	[142]
Lo et al.	2009	Propose and develop a "temperature-shift" strategy of cellulosic materials based bacterial hydrolysis, with the aim to improve production of reducing sugar.	[143]
Lo et al.	2009	Evaluate the efficiency of enzymatically hydrolysed rice husk with seven different hydrogen producing pure bacterial isolates to produce hydrogen via fermentation.	[144]
Prakasham et al.	2009	Report the utilisation of untreated mixed renewable agricultural waste (including rice husk, corn husk and ground nut shell) with buffalo dung compost to produce hydrogen.	[145]
Lo et al.	2010	Study a dual stage approach of combining feedstock pretreatment/hydrolysis and dark hydrogen fermentation to produce hydrogen from Xylan and rice straw via.	[146]
Nguyen et al.	2010	Report the study of utilising chemically pretreated Korean rice for thermophilic hydrogen fermentation by *Thermotoga neapolitana*.	[147]
Cheng et al.	2011	Study the hydrogen production from microwave-assisted alkali pretreated rice straw in enzymatic hydrolysis, by using combined dark and photofermentation.	[148]

production based on lignocellulosic biomass is largely limited to the pilot plant scale [130].

5.2.3. Hydrogen production via fermentation

Hydrogen production from fermentation of agricultural wastes is a relatively new research area as compared to the well-established anaerobic digestion. During fermentation, anaerobic bacteria ferment carbohydrates to produce hydrogen, volatile fatty acids and carbon dioxide. The fermentation process can be divided into photo-fermentation and dark fermentation where different types of bacteria function under different operating conditions. Hallenbeck and Benemann present the fundamental mechanisms of biological hydrogen production and their respective limiting factors [139]. Argun and Kargi compare bio-hydrogen production processes under different operating modes including the dark fermentation, the photo-fermentation and the combined dark and photo fermentation in order to identify the operating mode that gives the highest hydrogen formation rate and yield [140].

Table 12 shows the relevant researches associated with utilisation of rice straw and rice husk to produce hydrogen via fermentation process. Biomass fermentation with carbohydrates such as rice or other agricultural wastes is a promising route to produce hydrogen. Further increase in the hydrogen production yield to an economically feasible level, coupled with continuous development of industrial scale operations are however still needed.

6. Conclusion

Rice straw and rice husk are the main agricultural wastes (or biomasses) from rice. In many countries, these biomasses have great potential to be converted into energy in order to meet the countries' energy demands. China, India, Indonesia, and other rice-producing countries can enjoy the environmental and economic benefits from utilisation of rice straw and rice husk as sources of renewable energy. Heat and electricity from cogeneration systems could be used to meet the energy demands of local rice mills. Alternatively, excess electricity can be exported to the national grid. Other potential sources of energy from rice husk and rice straw that can be used for heating and power generation include methane and hydrogen generated via various biomass conversion processes. Ethanol is another important source of energy derived particularly from rice straw. It is typically used for public transportations, and has potential to reduce dependency on fossil fuels. Despite all the potential benefits, further research is still required on optimal allocation of rice straw and rice husk resources in rice mills as well as on industrial commercialisation of these technologies.

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